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Short communication

Comparison of gradability performance of fuel cell hybrid electric and internal-combustion engine vehicles

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HIGHLIGHTS

► Gradability performance comparison between (4WD) FC hybrid vehicle and ICE vehicle.
► Different FC parameters affecting vehicle gradability performance are studied.
► FCV performance can be increased by controlling FC parameters.

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ABSTRACT

Fuel cell vehicles are currently undergoing extensive research and development due to their potential for low emissions and high efficiency. Fuel cells are rapidly appearing not only in on-road vehicles but also in off-road vehicles. Off-road vehicles require special geometrical and performance parameters to be able to work in different road conditions. Gradability is one of the most important parameters in off-road vehicle performance which is defined as vehicle's ability to climb a grade at a given speed. This paper presents a comparison study between four-wheel drive (4WD) fuel cell hybrid electric vehicle gradability performance and internal-combustion engine (ICE) 4WD vehicle using Matlab/Simulink software.

1. Introduction

Fuel cell hybrid electric vehicles are based on the same architecture as conventional internal combustion, however, with a fuel cell stack and electric motor instead of an ICE as the primary source of mechanical power for the vehicle. This design offers many of the same benefits to fuel cell vehicle designers; the hybrid design increases vehicle fuel efficiency. However, where hybrids are primarily motivated from an emissions perspective with internal combustion, cost reduction is often a major motivation with fuel cell designs.

In fuel cell hybrid vehicles, mechanical energy is produced from electric motor using the electricity generated from chemical reaction inside the fuel cell. There are different kinds of fuel cells of which PEM and SOFC are the most important ones. PEM fuel cells are the most suitable in automotive applications for their high power density, low operating temperature and quick start capability.

In fewer than 10 years, fuel cell vehicles have been upgraded from ordinary research novelties to operating prototypes and demonstration models. Government and industry in development countries, at the same time, have cooperated to invest billions of dollars in partnerships intended to commercialize fuel cell vehicles within the beginning of the 21st century.

Increasing research in fuel cell and its application in the automobile industry provide an appropriate background for remarkable research in this field, especially in PEM fuel cells. For example, Doss and his colleague in 1998 developed a model for fuel cell systems to demonstrate power generation in which the temperature of the fuel cell was lower than 300 K [1].

In 1999, Quyang studied five different fuels like liquefied natural gas, liquefied oil gas, methanol, hydrogen, de ethyl ether, fixture

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Table 1
Developed models specification.

Vehicle model	Specification
4WD internal-combustion engine vehicle, Fig. 2.	- Generic engine of 100 kW. - Torque converter with mechanical gearbox. - Front and rear differential.
4WD fuel cell vehicle, Fig. 3.	- 400 Cells, 288 Vdc, 100 kW proton exchange membrane (PEM) fuel cell stack. - Electrical motor of a 288 Vdc, 100 kW interior permanent magnet synchronous machine (PMSM). - Electric battery of 13.9 Ah, 288 Vdc, 25 kW lithium-ion battery.

tropes diesel and electricity in spark, diesel, hybrid electric, electric, and fuel cell vehicles. The results show that fuel cell vehicle has high performance and low pollution [2].

In 2000, the design and structure of fuel cell vehicle was tested using a device consisting of a small fuel cell stack for producing a requested average power and a battery for providing power in different moving conditions [3]. In 2001, a model for PEM fuel cell was presented to study fuel cell stack reactions using physical chemistry relationships [4].

In 2004, the transient phenomena in fuel cell PEM system were presented by a mathematical model for simulating [5]. In 2006, Kim and his colleague developed a strategy for power management to optimize fuel consumption in a fuel cell hybrid vehicle [6].

In 2009, Tremblay et al proposed a new approach for fuel cell modeling. The model is a generic model and able to simulate the performance of any fuel cell types fed with hydrogen and air. This model is integrated in SimPowerSystems™ and SimDriveline™ and used in the simulation of a Fuel Cell Vehicle (FCV). The vehicle is modeled with the characteristics of the Honda FCX-Clarity [7].

To continue from this previous study, in this paper, a comparison study of gradability performance on Honda FCX-Clarity vehicle powered by ICE and fuel cell stack/electric motor. The various effects in vehicle gradability performance such as fuel cell power, operating temperature, air flow, air supply pressure and fuel supply pressure are all studied.

2. The vehicle model analysis

Two multi-domain simulation of a vehicle power train based on SimPowerSystems and SimDriveline models are developed to compare ICE vehicle with FC vehicle performance, as shown in Table 1.

We will discuss one important parameter which is called gradability performance; it will be tested using the two developed models starting from the rest on ascending a 15° incline road as shown in Fig. 1, the tested vehicle specifications are shown in Table 2.

The overall reaction of the proton exchange membrane fuel cell (PEMFC) is given by:

Anode: $H_2 \rightarrow 2H^- + 2e^-$

Cathode: $2H^+ + 2e^- + \frac{1}{2} O_2 \rightarrow H_2O$

The energy potential (the Gibbs free energy) of this reaction is given at standard temperature and pressure by [8]:

$$\Delta g^\circ = \Delta h^\circ - T_o \Delta s^\circ \tag{1}$$

Where:

Δg° Reaction Gibbs free energy
Δh° Reaction enthalpy
Δs° Reaction entropy
T_o Standard temperature (298 K)

The standard-state thermodynamic voltage is given by:

$$E^\circ = \frac{\Delta g^\circ}{zF} \tag{2}$$

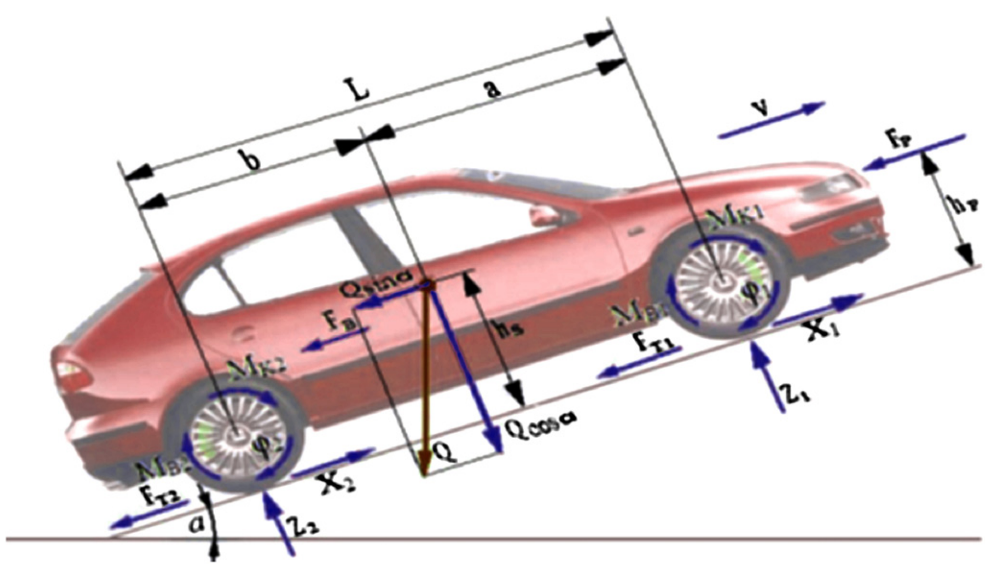

Fig. 1. System of forces and moments acting on the vehicle Q – vehicle weight, X_1, X_2 – longitudinal forces, F_T – rolling resistance, F_B – inertial force, F_P – aerodynamic drag force, Z_1, Z_2 – vertical forces, M_{K1}, M_{K2} – external torque wheel (driving torque or braking), M_{B1}, M_{B2} – moment of inertia wheel and related items, L – wheelbase, a, b – axis distance from the center of mass, v – vehicle velocity, h_p – pressure center distance above the road surface, h_s – height of center mass location, α – angle of the road, $\varnothing_1$, $\varnothing_2$ – angles of wheels' rotation.

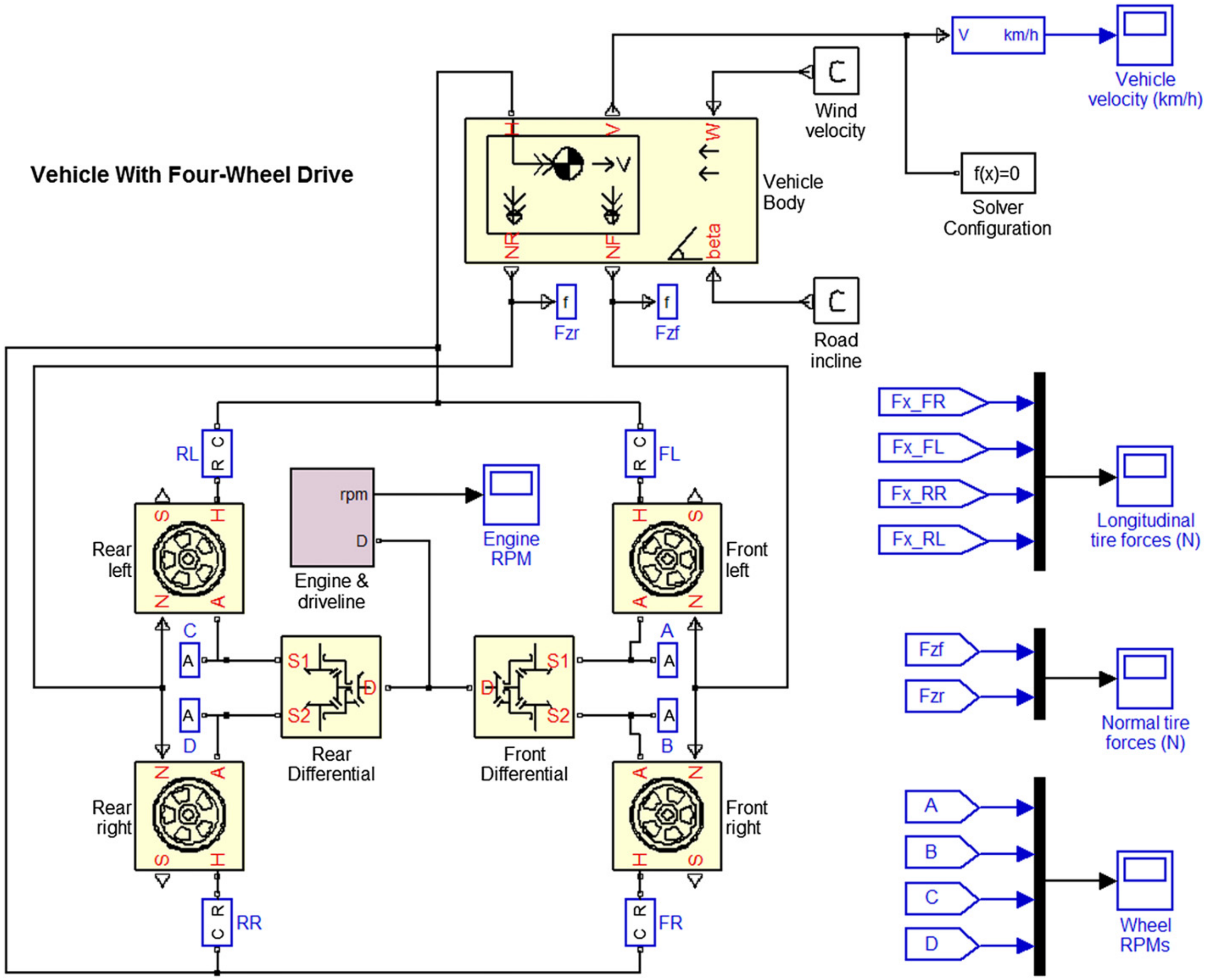

Fig. 2. 4WD ICE vehicle simulation model.

Where:

E° = standard thermodynamic voltage
F = Faraday's constant (96,485A s mol^{-1})
Z = number of moving electrons

At nonstandard-state condition, the thermodynamic voltage varies with pressure and temperature. It is given by the Nernst equation as follows:

The cell efficiency is usually given with respect to the lower heating value (LHV), that's with the assumption that the water produced is in steam form. The efficiency is given by:

$$\eta = \frac{zFU_{f_{H_2}}V}{\Delta h^\circ(H_2O(gas))} \times 100 \quad (4)$$

Where:

P = Cell output power

$$E_n = \begin{cases} 1.229 + (T-298)\cdot\dfrac{-44.43}{zF} + \dfrac{RT}{zF}\,\mathrm{Ln}\left(P_{H_2}P_{O_2}^{1/2}\right) & T \le 100\,^\circ\mathrm{C} \\ 1.229 + (T-298)\cdot\dfrac{-44.43}{zF} + \dfrac{RT}{zF}\,\mathrm{Ln}\left(\dfrac{P_{H_2}P_{O_2}^{1/2}}{P_{H_2O}}\right) & T > 100\,^\circ\mathrm{C} \end{cases} \quad (3)$$

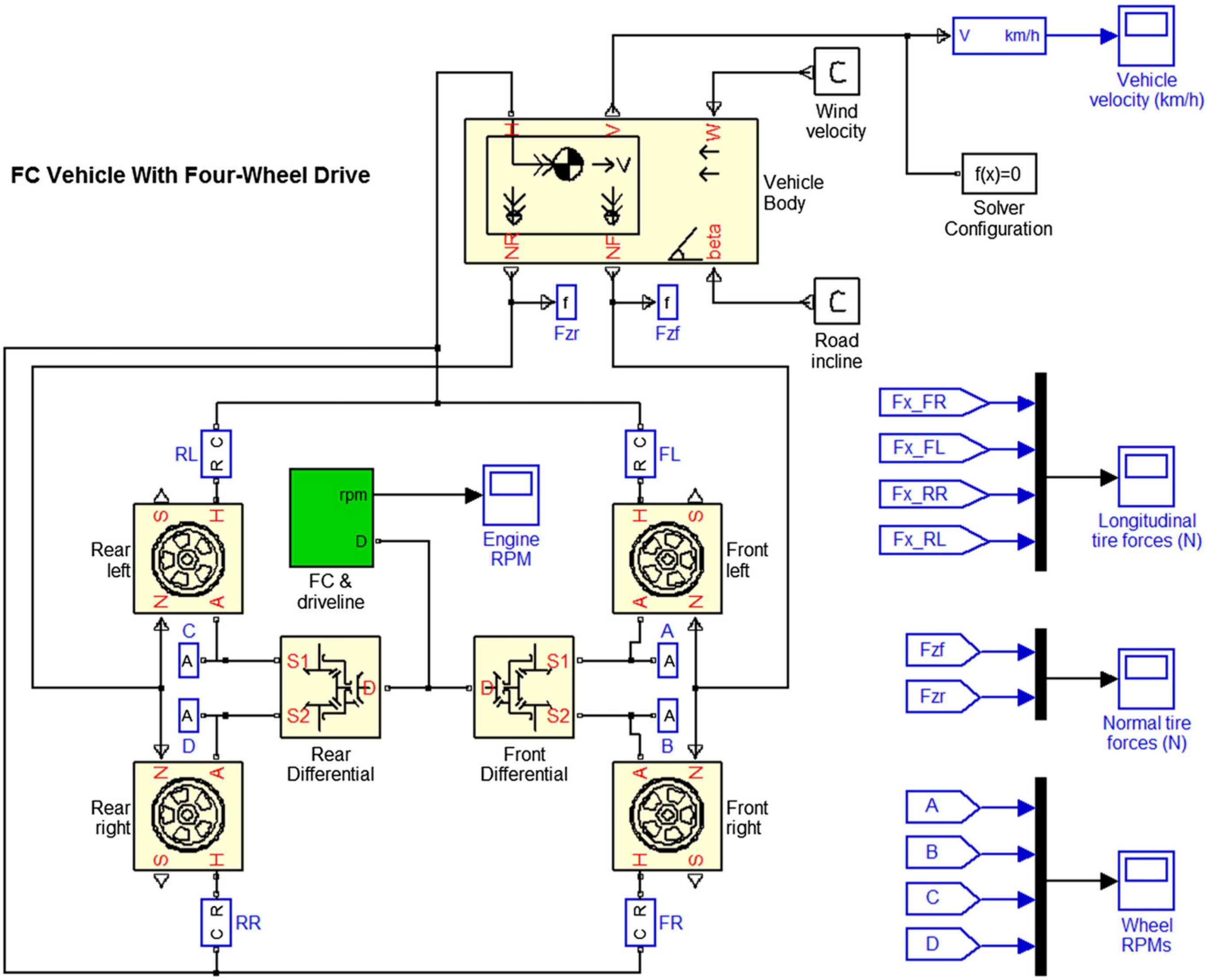

Fig. 3. 4WD FC vehicle simulation model.

$\Delta h^\circ(H_2O(gas))$ = Reaction enthalpy of water vapor (241.83 kJ mol^{-1})
V = Cell output voltage

The actual cell voltage can be deduced by combining the Nernst voltage and the losses as follows:

$$V = E_n - A\,\mathrm{Ln}\left(\frac{i_{fc}}{i_0}\right) \cdot \frac{1}{sT_d + 1} - ri_{fc} \tag{5}$$

For a stack with N cells in series, the stack voltage is given by:

$$V_{fc} = N \cdot \left(E_n - A\,\mathrm{Ln}\left(\frac{i_{fc}}{i_0}\right) \cdot \frac{1}{sT_d + 1} - ri_{fc}\right) \tag{6}$$

3. Results

The gradability performance comparison was carried out in terms of three different parameters; vehicle speed, longitudinal tire forces and normal tire forces as shown in Figs. 4–6.

Generally, the gradability performance of fuel cell vehicle is better than the ICE one, but we can notice that initially the two vehicles roll backwards until the engine or electric motor develop sufficient torque to counter the slope and the engine performance better than the FC vehicle because the fuel cell started to provide power but is not able to reach the required power due to its large time constant so that the FC vehicle depends on the electric battery power (25 kW).

From the previous results, we need more clarification of the different parameters that could affect the FC vehicle performance like fuel cell power, operating temperature, air flow, air supply pressure and fuel supply pressure.

In this paper, the effect of various fuel cell parameters like operating temperature, nominal air flow, Nominal air supply pressure and Nominal fuel supply pressure on vehicle gradability performance will be discussed as follows: Study on the effect of the fuel cell operating temperature was carried out using the FCV Simulink model in four levels from 25 to 85 °C. while keeping the other fuel cell parameters constant. A decrease in the vehicle speed and tire forces with time is viewed in Fig. 7.

Table 2
Vehicle specifications.

Specification	Value	Unit
Mass	1500	kg
No. of wheels per axle	2	
Horizontal distance from CG to front axle	1.4	m
Horizontal distance from CG to rear axle	1.6	m
CG height above ground	0.5	m
Frontal area	3	m^2
Drag coefficient	0.4	
Initial velocity	0	$m\ s^{-1}$

In other words, the performance of the FCV is decreased under elevated cell operating temperature. The decrease of the fuel cell performance with the increase of the cell temperature can be explained by at lower stack temperature, the relative humidity inside the fuel cell stack is higher, so the cell's membrane is more humid. This increases the membrane conductivity which decreases the stack resistance (that means less resistive losses).

Study on the nominal fuel supply pressure effect was carried out in three levels from 2 to 4 bar and air supply pressure of 3 bar while

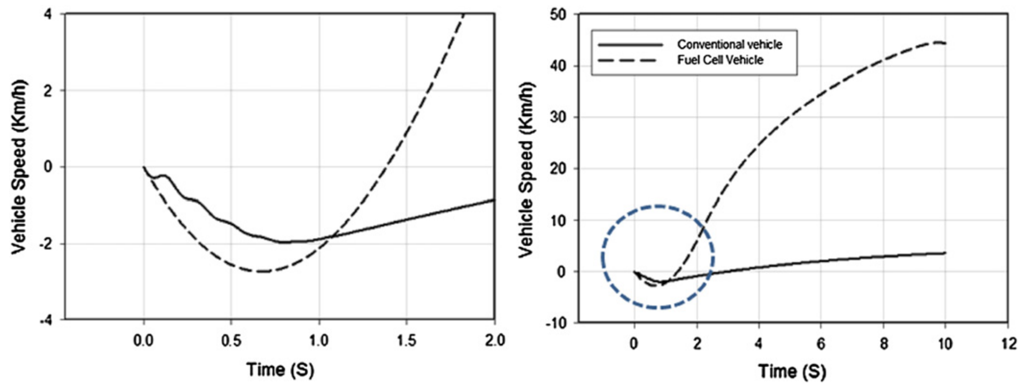

Fig. 4. ICE & FC vehicle speed on grade 15°.

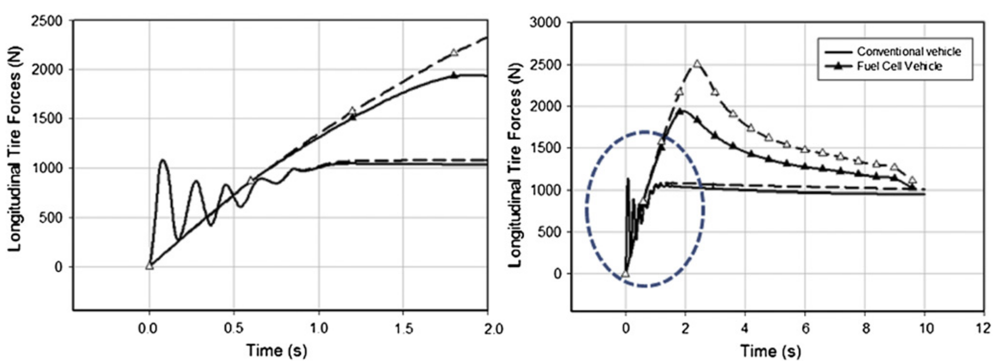

Fig. 5. ICE & FC longitudinal tire forces on grade 15°. *Front tires* ; *rear tires* .

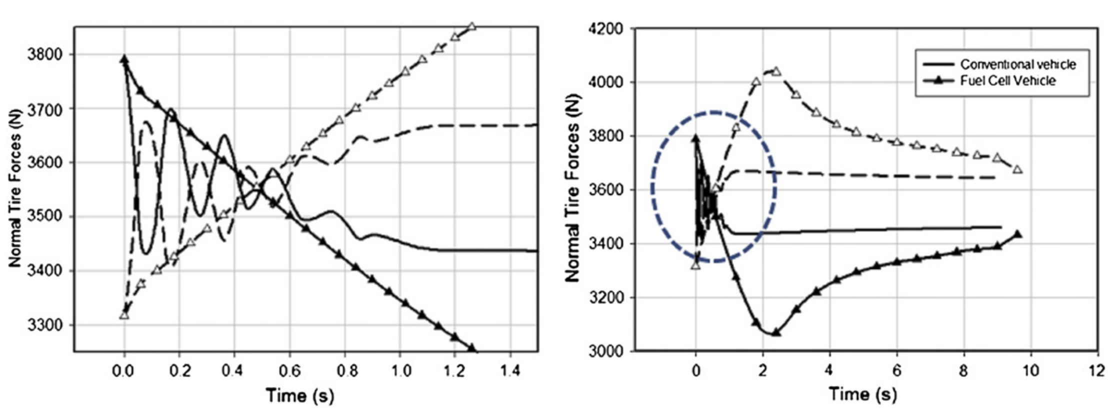

Fig. 6. ICE & FC normal tire forces on grade 15°. *Front tires* ; *rear tires* .

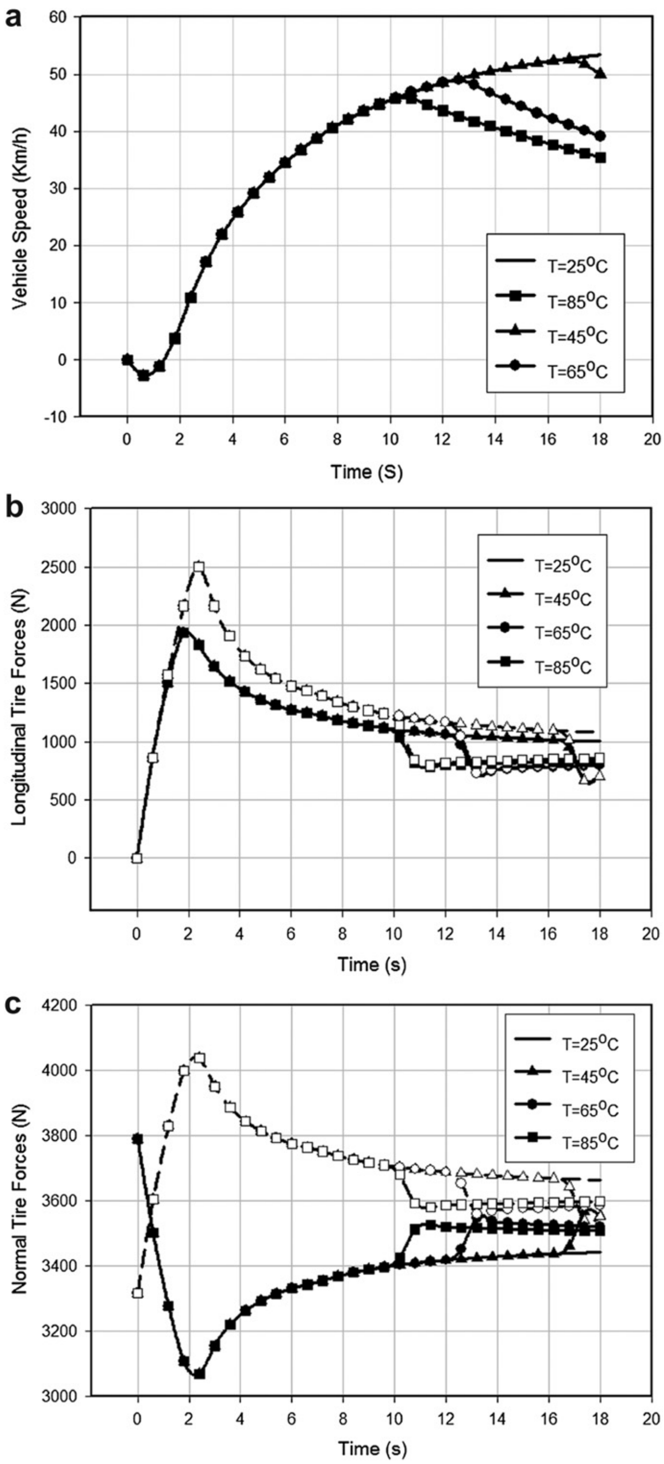

Fig. 7. Comparing FCV gradability performance on different operating temperature: a) vehicle speed, b) longitudinal tire forces, c) normal tire forces. *Front tires* ———; *rear tires* — — — — —.

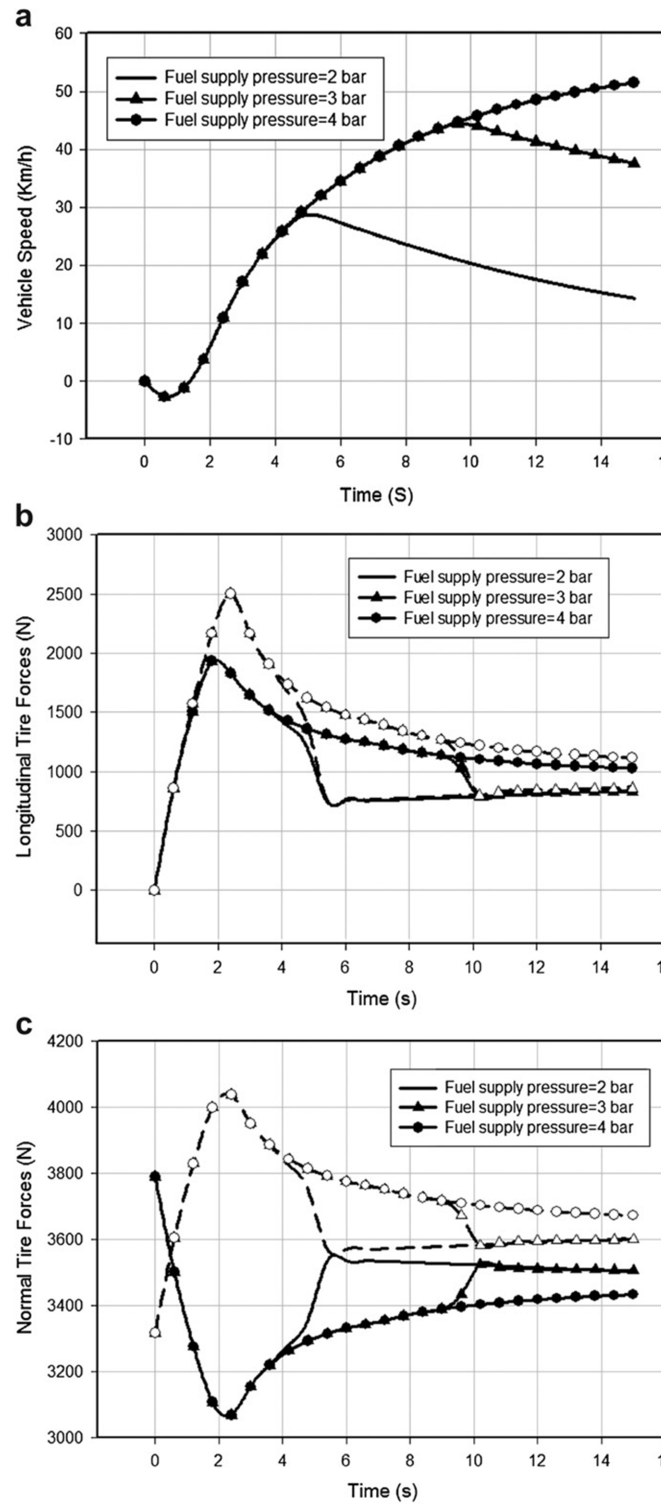

Fig. 8. Comparing FCV gradability performance on different fuel supply pressure: a) vehicle speed, b) longitudinal tire forces, c) normal tire forces. *Front tires* ———; *rear tires* — — — — —.

keeping the other fuel cell parameters constant. An increase in the vehicle speed and tire forces with time is viewed in Fig. 8.

The increase of the fuel cell performance with the increase of the nominal fuel supply pressure can be explained by that the open circuit voltage for hydrogen fuel cells increases with increasing hydrogen pressure as shown in equation (3) which can be derived from Nernst equation assuming that all pressures are given in bar.

Study on the nominal air supply pressure effect was carried out in three levels from 2 to 4 bar and fuel supply pressure of 3 bar while keeping the other fuel cell parameters constant. A decrease in the vehicle speed and tire forces with time is viewed in Fig. 9.

The decrease of the fuel cell performance with the increase of the nominal air supply pressure can be explained by that, while the open circuit voltage for hydrogen fuel cells increases with

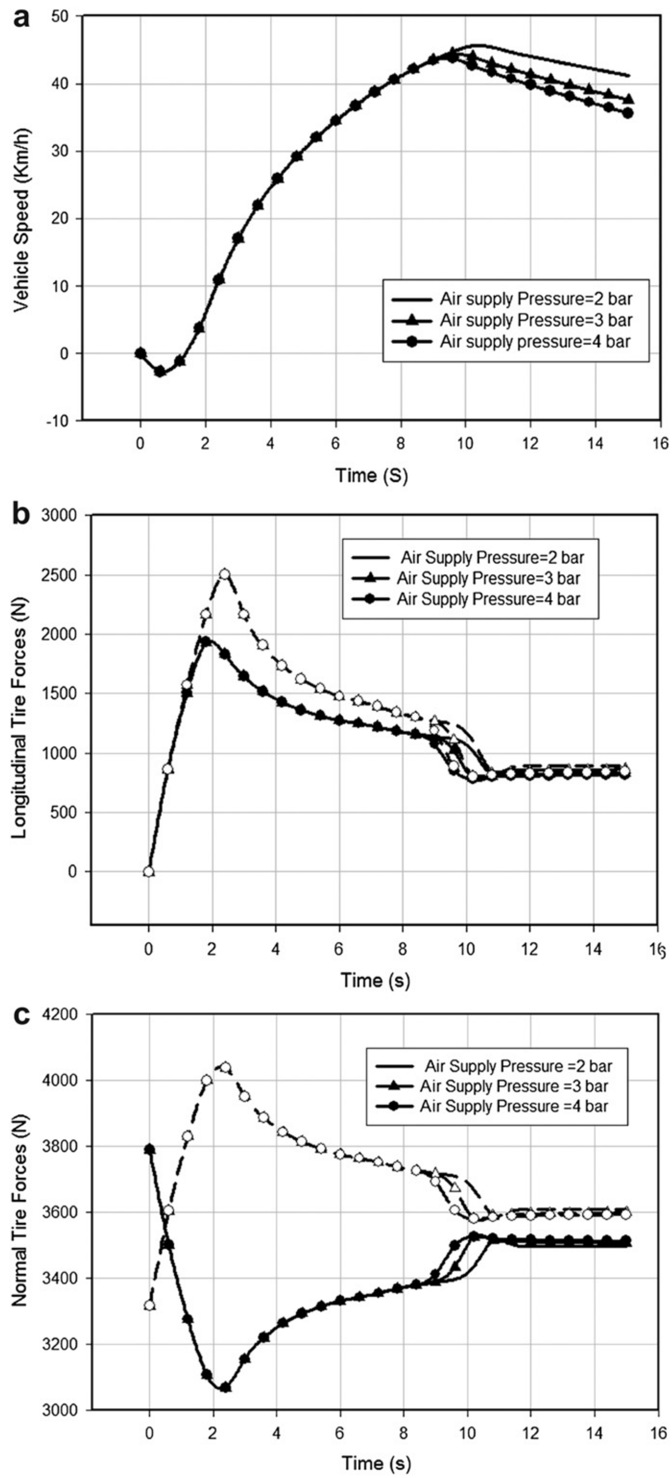

Fig. 9. Comparing FCV gradability performance on different air supply pressure: a) vehicle speed, b) longitudinal tire forces, c) normal tire forces. *Front tires* ———; *rear tires* — — — — —.

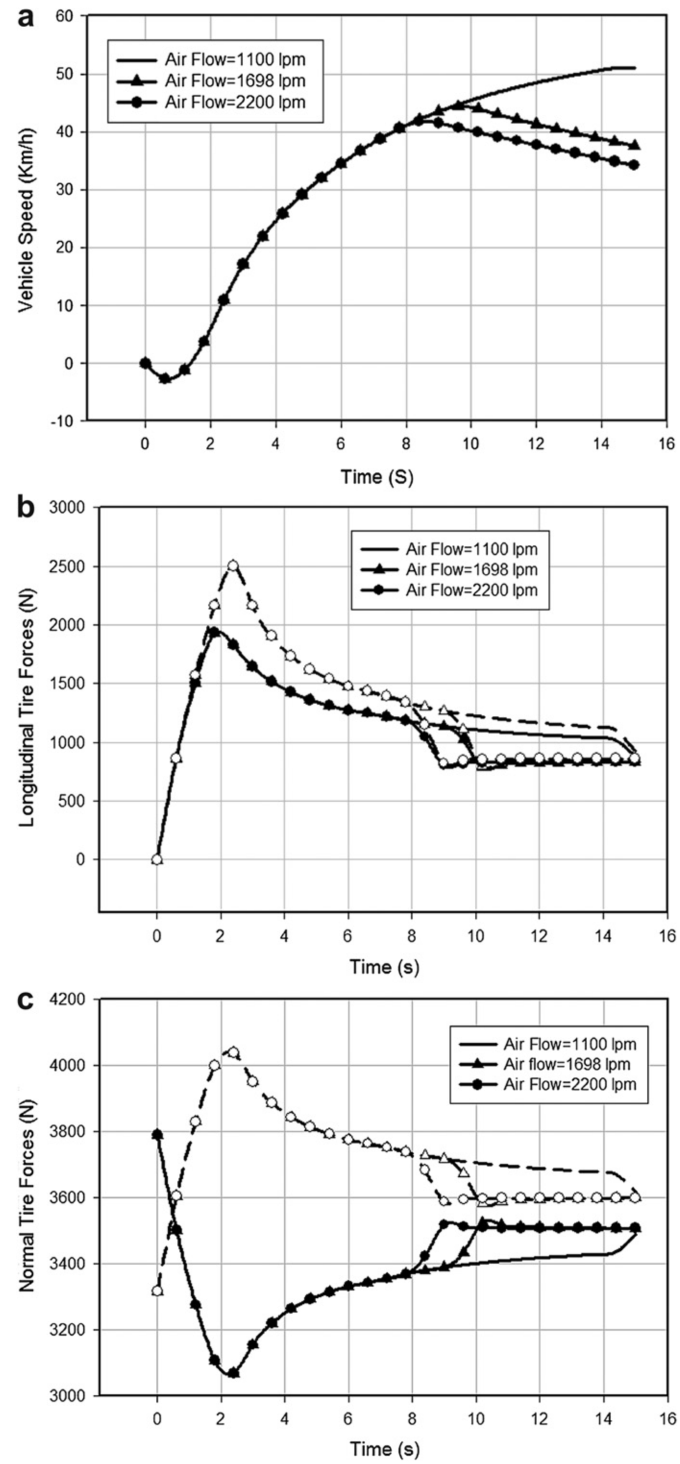

Fig. 10. Comparing FCV gradability performance on different air flow: a) vehicle speed, b) longitudinal tire forces, c) normal tire forces. *Front tires* ———; *rear tires* — — — — —.

increasing oxygen pressure as shown in equation (1), but actually to obtain this high air pressure the power demand of the air compressor increased by a certain rate higher than the rate of increasing the output power of the fuel cell. So the FCV performance decreased with increasing the air supply pressure.

Study on the nominal air flow effect was carried out in three levels from 1100 to 2200 lpm while keeping the other fuel cell parameters constant. A decrease in the vehicle speed and tire forces with time is viewed in Fig. 10.

The decrease of the fuel cell performance with the increase of the nominal air flow can be explained by that the compressor workload is substantially increased to increase the air mass flow, the power demand for compressor was higher than the increase in fuel cell output power, so that we found from the simulation results

a certain decrease in the FCV performance with increasing the air mass flow. Also, the effect of change of air flow on FCV performance is higher than the effect of change of the air supply pressure.

4. Conclusions

In this paper, a comparison between 4WD hybrid vehicle using fuel cell and 4WD conventional vehicle using ICE is investigated concentrating on the gradability performance of the vehicle in terms of main three parameters; vehicle speed, longitudinal tire forces and normal tire forces. From simulation results, we can say that FCV gradability performance is better than the conventional one except in the beginning of the climbing action because of the dependence on the electric battery in the FCV.

The FCV performance is affected by parameters such as ambient conditions and duty cycle. Here, a clarification study of the effect of different fuel cell parameters, operating temperature–nominal fuel supply pressure–nominal air supply pressure–nominal air flow, on the FCV performance was carried out.

From the simulation results, we can outline that the FCV performance can be increased by increasing fuel supply pressure and decreasing air flow and air supply pressure and operating in lower temperature or in other words increasing the efficiency of the cooling system.

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